Status of NEPP Advanced Sensors Efforts

Presented by Cheryl Marshall (NASA-GSFC)

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[TowerJazz (Scott Jordan), NRL (Steve Buchner), SoloHI team]

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Outline

- **Primary Goals**
  - **Cryogenic Latch-up (LU)**
  - **Infrared (IR) Lessons Learned**
  - **Radiation response of emerging technologies**
- **Current Status**
- **Preliminary FY12 NEPP Plans**
  - **Submitted Phase I IRADs**
  - **Synergy with SoloHI**
- **Summary**

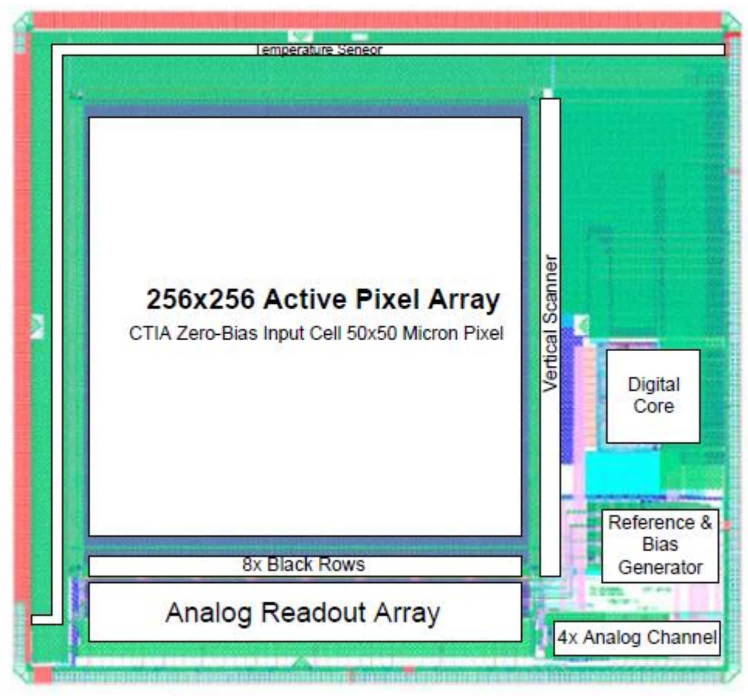
Cryogenic Latchup (LU) Goals

- Access cryogenic latchup concerns for missions with CMOS technology (e.g. read-out integrated circuits (ROICs), ASICs, etc.)
- Identify and characterize relevant cryogenic test structures for key technology nodes.
  - Begin development of TCAD modeling with validated temperature-appropriate models.
- Complete data analysis of cryogenic ROIC and R.T. IBM 130 nm SEL data:
  - Understand the depth dependence of cryogenic SEL via matrix of MeV/u, R_{eff}, and LET $_{eff}$ data as compared to energy deposition calculations.
  - Verify that test structure instrumentation provides data quality required for TCAD modeling
    - Begin modeling effort
- Jazz 180 nm test structures for future work
  - Designed and currently in fab
  - IRAD to develop laser LU test capability?

- Dewar to be used for laser testing and 13µm HgCdTe tests. New ZnSe port being designed for radiometry characterization of long wave infrared (LWIR) detectors.

NEPP FY11 Goals, cont.

- IR Lessons Learned document
- Investigation of proton-induced dark current annealing in light of recent HST WFC3 on-orbit data, recent DoD JMAPS Si PIN data, future flight projects
  - Re-visit of earlier HST/NEPP experiment on WFC3 e2v CCD array.
- Study of 1/f noise of increasing importance with technology scaling
  - Future SoloHI leveraging opportunity
- Commercial CMOS sensor planning with JPL in light of recent GSFC project base-lining Aptina or Omnivision arrays.
- Dewar instrumentation & full characterization (including radiometry) of hardened LWIR HgCdTe sensor array/ROIC



- ROIC used by Air Force on Space Tracking and Surveillance System (STSS)
- Active array: 256x256 active input cells on 50 µm centers

Summary of FY11 Plans

- Partners: Georgia Tech, Vanderbilt, Naval Research Lab, Air Force Research Lab, GSFC Detector Characterization Lab, & GSFC IRAD
- Planned tests, DUTs & test reports:
  - 1st Quarter
    - Final NEPP/IRAD report & poster presentations of cryogenic LU work
    - IR Lessons Learned (ALL QUARTERS!)
  - 2nd Quarter
    - Analysis of remainder of TAMU data on ROIC & test structures
    - Analysis & understanding of recent HST & JMAPS data (Also 3rd & 4th Qtrs)
    - Dosimetry investigation at RPI LINAC for cryogenic LWIR sensor test
  - 3rd Quarter
    - Design of Jazz 180 nm LU test structures for electrical, laser and heavy ion characterization
    - Preliminary design of cryogenic laser test capability
    - Dewar modifications for LWIR HgCdTe array/ROIC test
  - 4th Quarter
    - Complete IR Lessons Learned and Photonics Chapter
    - Complete LWIR HgCdTe measurements & final report
    - Package Jazz LU test structures and consider early Vanderbilt electrical LU studies in NEPP planning

Summary of Current Status

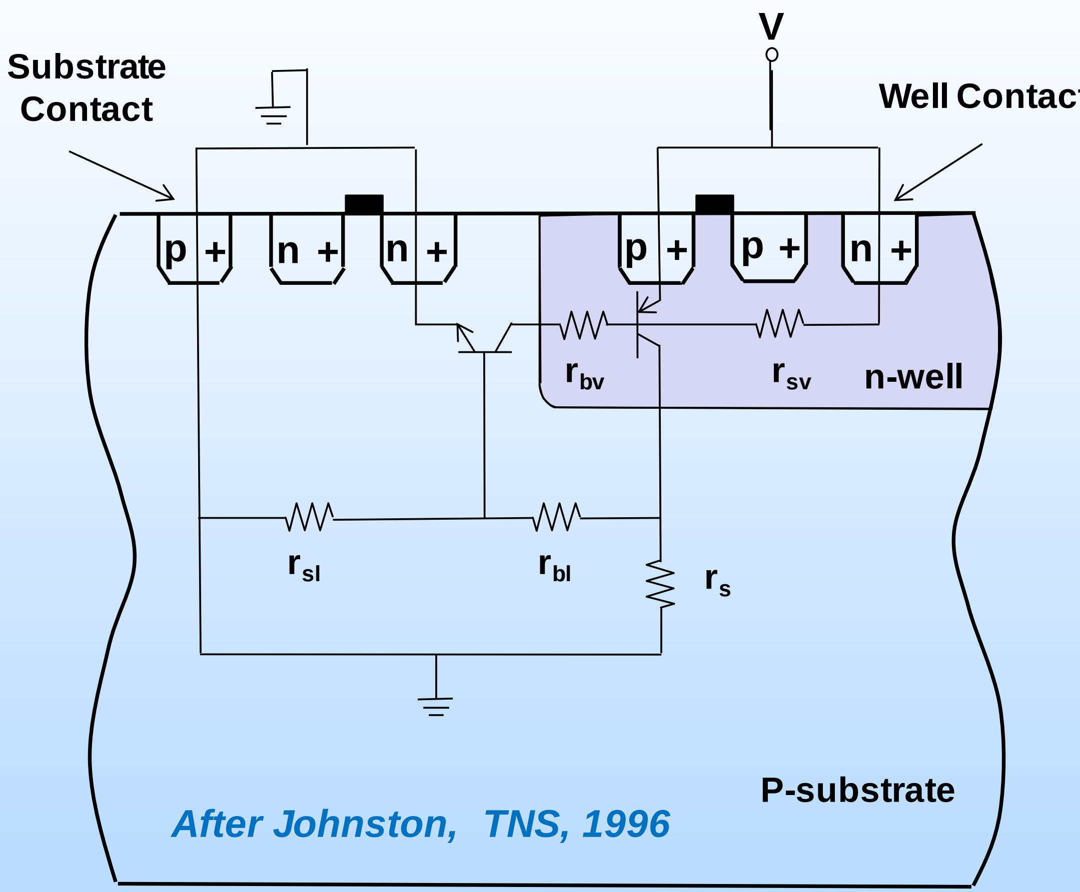
- **Accomplishments**
  - **Concept for dewar instrumentation for cryogenic radiation testing of hardened LWIR to cobalt 60, protons, heavy ions or *electrons*. EJSM lost funding but we acquired an IRAD.**
    - **Trip to RPI LINAC confirmed that conventional LINAC dosimetry will not suffice so real time Si PIN dosimetry planned internal to dewar.**
    - **Progress with acquisition of hardened Air Force technology from Teledyne.**
    - **Design for machine work (curved surface) on new ZnSe optical window in progress.**
    - **Test matrix design in progress based on earlier Air Force/NEPP proton data set.**
  - **Jazz has agreed to work with Vanderbilt & GSFC to provide space for custom 180 nm SCR LU test structures currently being defined. (Jonny & Nathaniel providing TID data in return.)**
  - **130 nm heavy ion SEL event data at 300 K ready for Georgia Tech.**
  - **Initial data review for HST WFC3 on-orbit data & JMAPS proton test complete.**
  - **SPIE papers difficult to collect this year, but submitted abstracts are high quality.**

- **Current status**
  - **Obtaining detailed Air Force ROIC information necessary for dewar instrumentation & are continuing with dewar modifications.**
    - **Full proton data set (LWIR HgCdTe) for all integration times will be sent to GSFC.**
  - **Design concept of Jazz 130 nm LU test structures underway. If Vanderbilt legal approval occurs within ~3 weeks, then Nathaniel Dodds (NASA GSRP graduate student currently at GSFC) can meet deadline for 6/14 foundry run with Si die available mid Sept.**
  - **Putting together technical package for Jim Waterman at NRL re cooperation in use of JMAPS Si PIN data.**
  - **Date for AFRL cryogenic SEL ROIC run still not set.**

Basics of Latchup Process

Cross coupled parasitic bipolar transistors inherent to CMOS Technology

- **Current produced by ion strike can forward bias the base emitter junction and begin the LU sequence**
- **Key device parameters for all temperature regimes:**
  - **Well & substrate resistivities**
  - **Well & substrate contact proximity**
  - **Minimum n+ - p+ , or cathode-anode spacing**

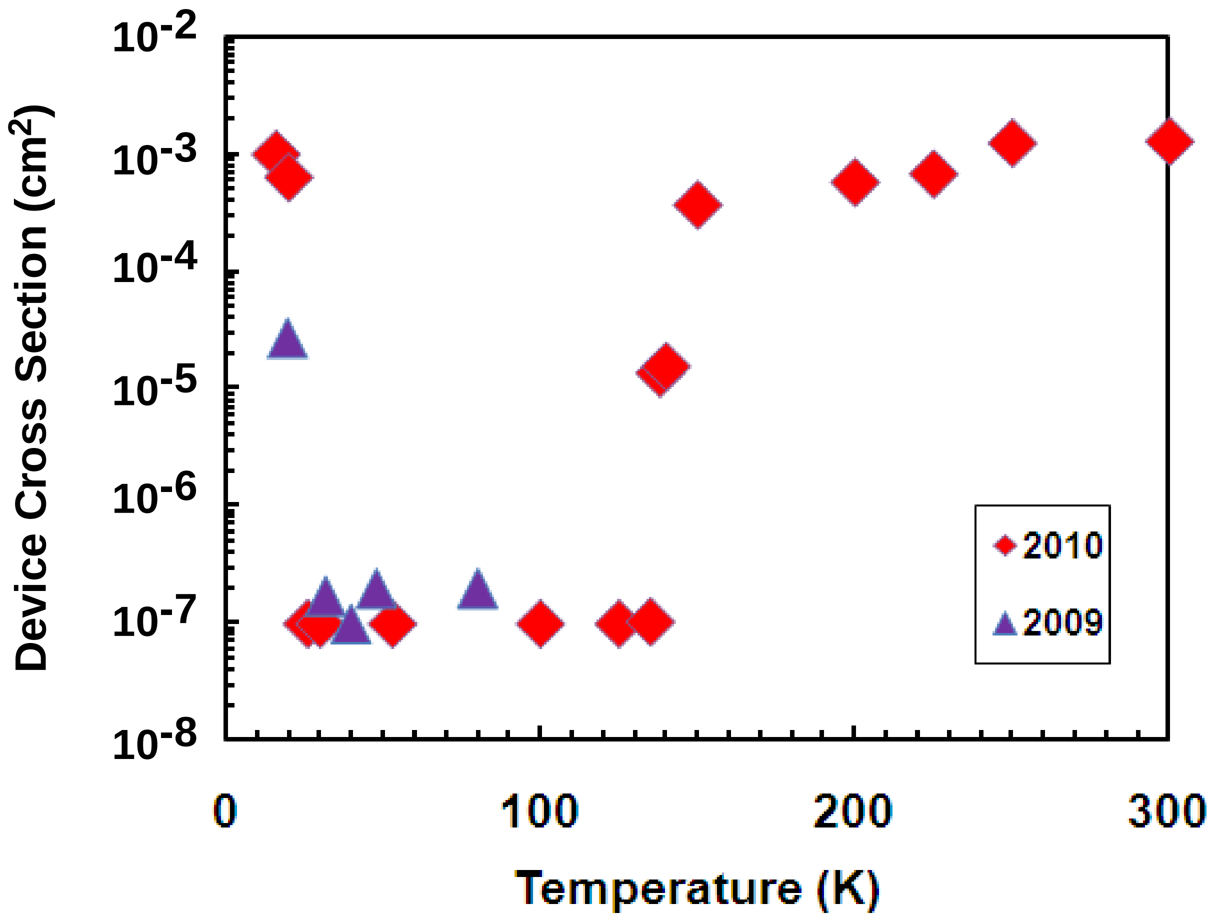


After Johnston, TNS, 1996

Temperature Dependence of Latchup

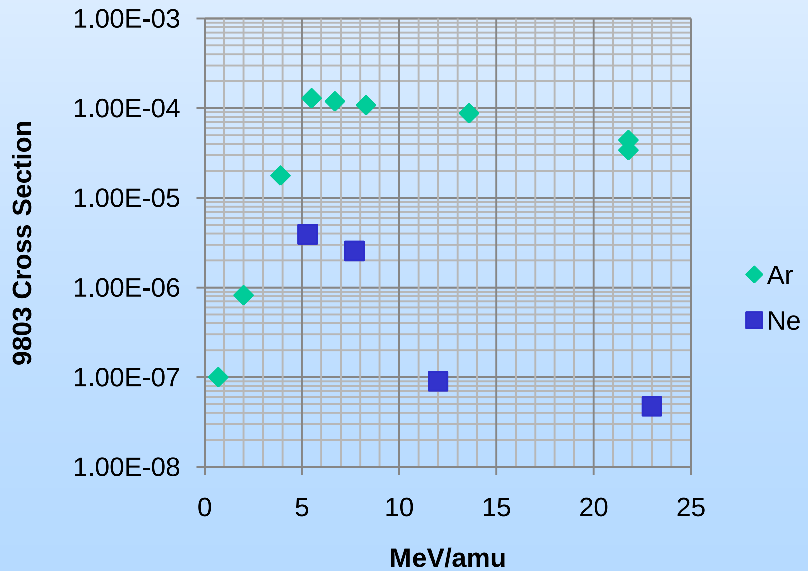
- **Two classes of SEL events**
- **Self quenching latch events observed in transition regions**
- **Cryogenic SEL >100 K observed for ROICs from 2 vendors**
- **Range of holding voltages & current levels during latch events observed**

0.5 µm bulk CMOS ROIC on p-Si

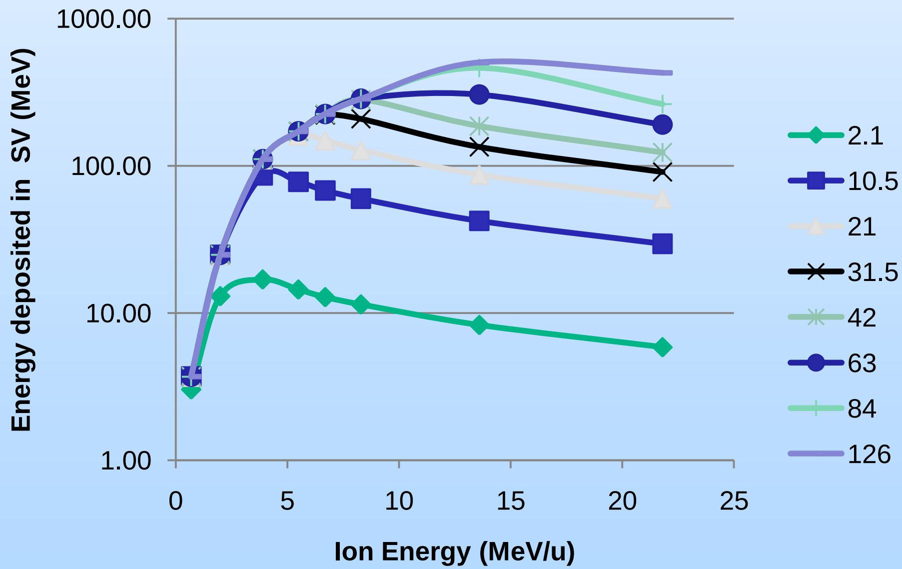


Understanding Deep Cryogenic Latchup

- **Further analysis of cryogenic SEL ROIC heavy ion data**
  - **Depositing even large amounts of energy very near the surface can trigger an SEL but it is not sustained. Data shows significant drop in SEL cross section for effective ranges below ~30 µm, indicating the importance of diffusion.**
    - **Attempting to correlate data with energy deposition calculations.**
    - **Nathaniel is currently working with nested sensitive volumes to see if sensible fits are possible.**

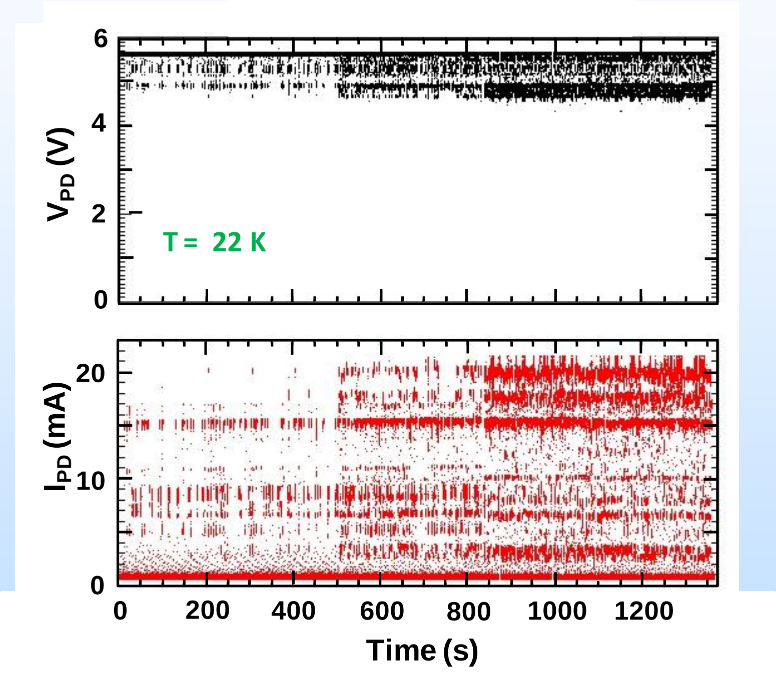


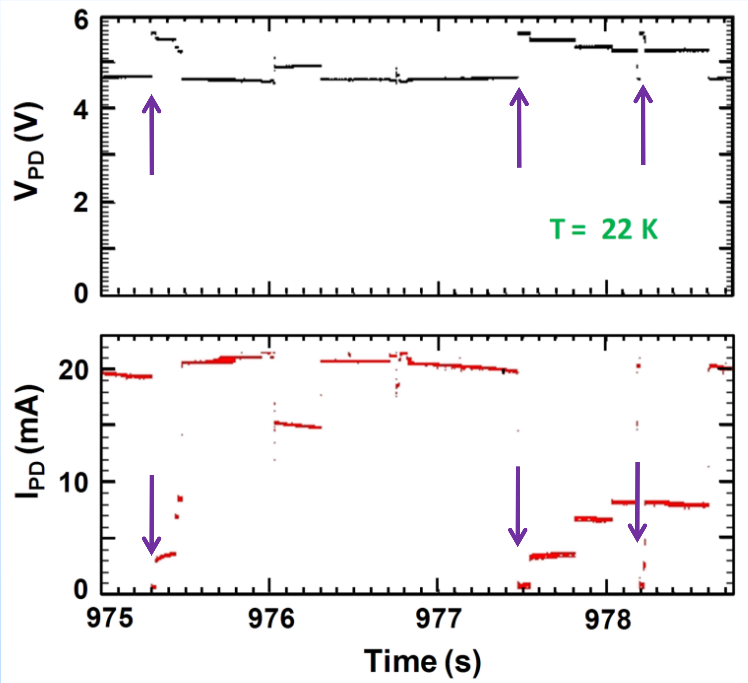
Energy deposited in Sensitive volumes of various thicknesses



Understanding Deep Cryogenic Latchup, *cont.*

- **Further analysis of cryogenic SEL ROIC heavy ion data**
  - **Discussions with COOLCAD to begin understanding SEL behavior at transistion regions.**
    - **It is possible that the shallow-level impact ionization currents lower the local electric field below the level required for impact ionization leading to an oscillatory behavior.**

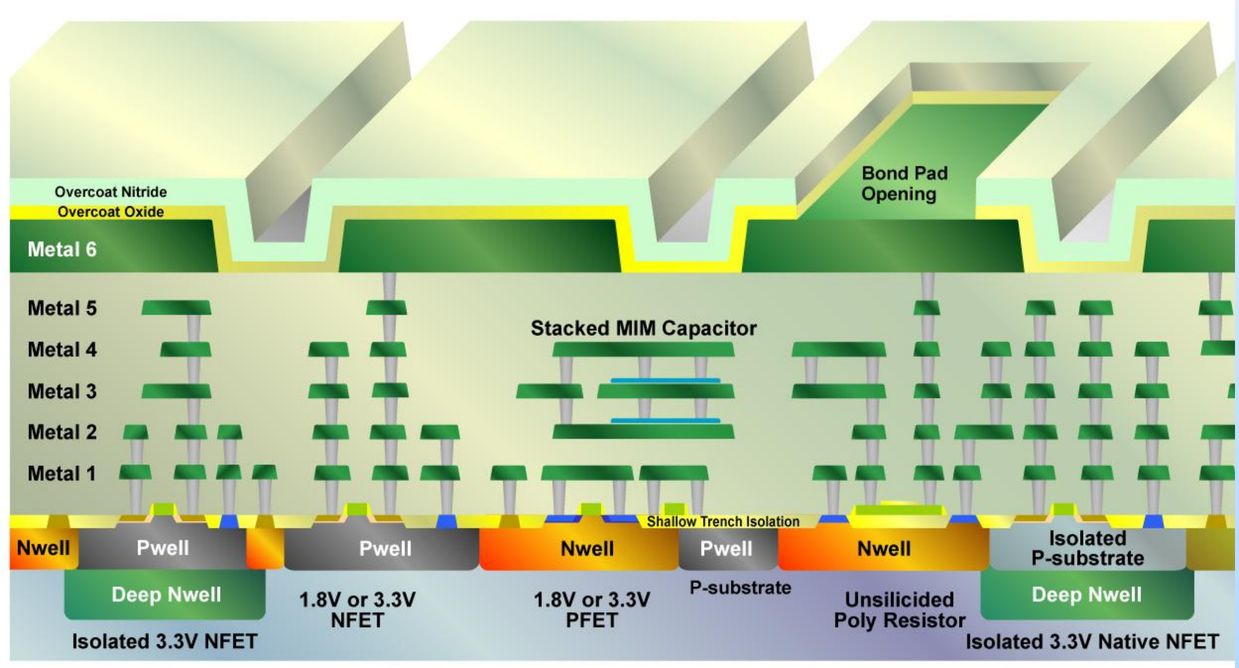




Almost continuous self-quenching high currents events at 22 K. Device returned to nominal operational conditions (V_{PD} = 5.7 V and I_{PD} ~0.5 mA) in between events or strings of events. Right plot is an expanded region with arrows showing where the device operation is normal. Similar behavior was observed at 24 K at 135 K.

New TowerJazz Latchup Test Structures

- **Why JazzTower CA18HD process?**
  - **Scaling is driven by digital trends that further the 'all digital ROIC' option but works against critical CMOS sensor and ROIC performance trades (full well, sensitivity, low noise, QE, etc.)**
  - **1.8 V core & options for 3.3 V or 5 V I/O.**
  - **Other key analog capabilities (high quality capacitors, thick metals, low noise active analog devices, deep n-well for substrate isolation (radiation plus too) sub-field stitching for larger die, cryogenic & relevant uniformity models.**



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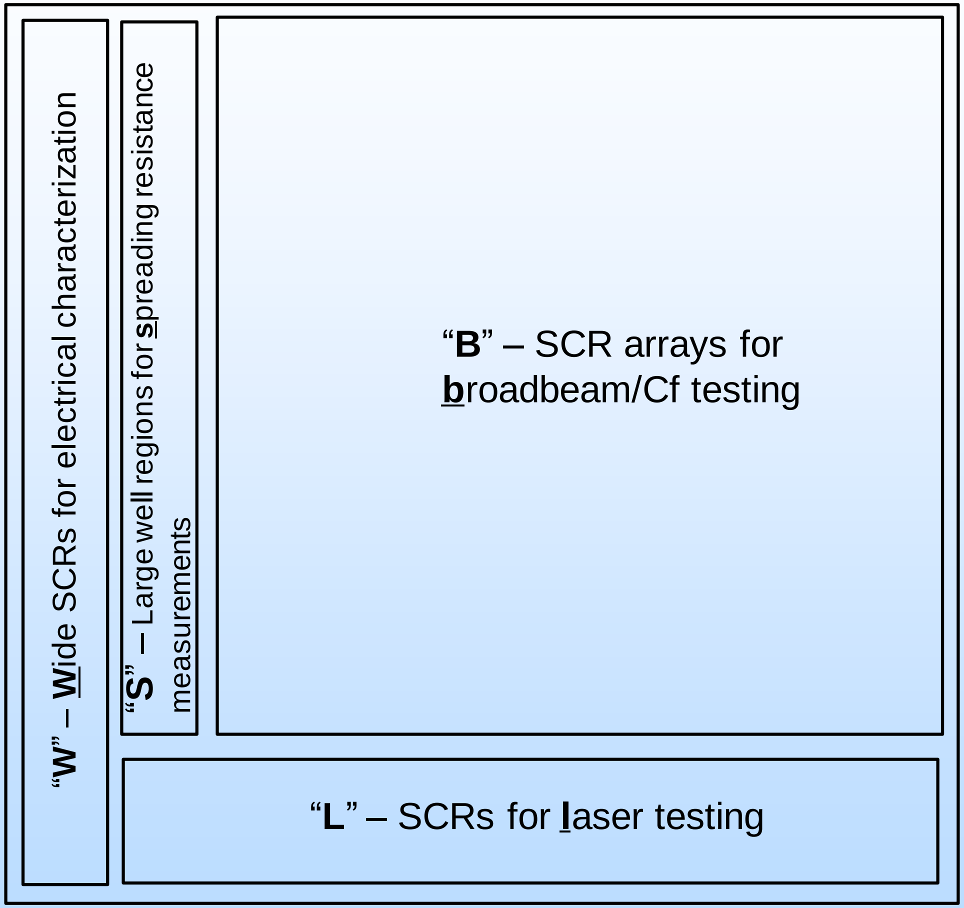
New TowerJazz Latchup Test Structures, *cont.*

- **Die area offered is 2.5 mm x 2.5 mm!!**
  - **50-55 die provided**
- **4 Blocks planned for our die area:**
  - **Wide Si controlled rectifiers (SCRS) for electrical LU**
  - **Large well region structures for spreading resistance measurements**
    - **Supports VU modeling & potential charge collection measurements**
  - **Largest die block for heavy ion testing to optimize cross section data from threshold through saturation**
  - **SCRs for laser testing**
    - **Fewer bond pads required as only one structure at a time is measured.**



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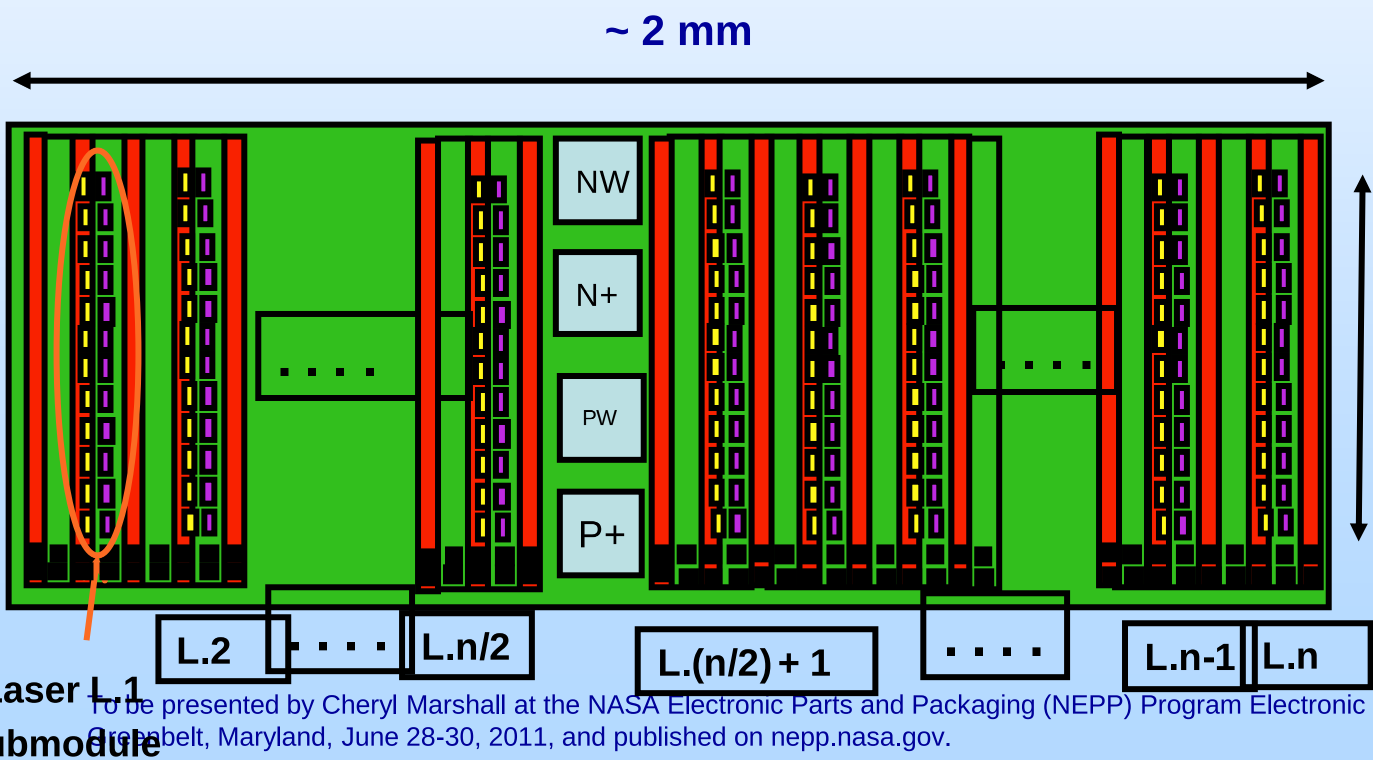
New TowerJazz Latchup Test Structures, *cont.*

- Flavors of SCR employed will depend on the block but can independently vary:
  - Anode-cathode spacing
  - Well contact density
  - Use of guard rings
  - Use of triple wells
- This permits a wide range of electrical and SEL susceptibility
- We benefit from diagnostic data from Jazz even though their test structures may not be optimal.



Each laser submodule consists of many identical SCRs at various distances from well contacts (max ~100 µm).

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Infrared Sensor Testing: Lessons Learned

- Practical figure of merits for IR sensor radiation testing
- Descriptions of measurements of key performance parameters
- Challenges of testing in a dewar (mods required!)
  - Reliability due to access & DUT cycle time, activation, heavy ion range, temperature effects, He at test facility, custom tables, etc.
- Cryogenic test set development
  - Temperature ramp rate, light, noise, thermal, radiometry
- Selected practical testing issues
  - Annealing
  - Signal contamination via activation & luminescence
- Data storage and analysis
  - In situ frame collection leads to 10’s of Gbytes
  - Event identification

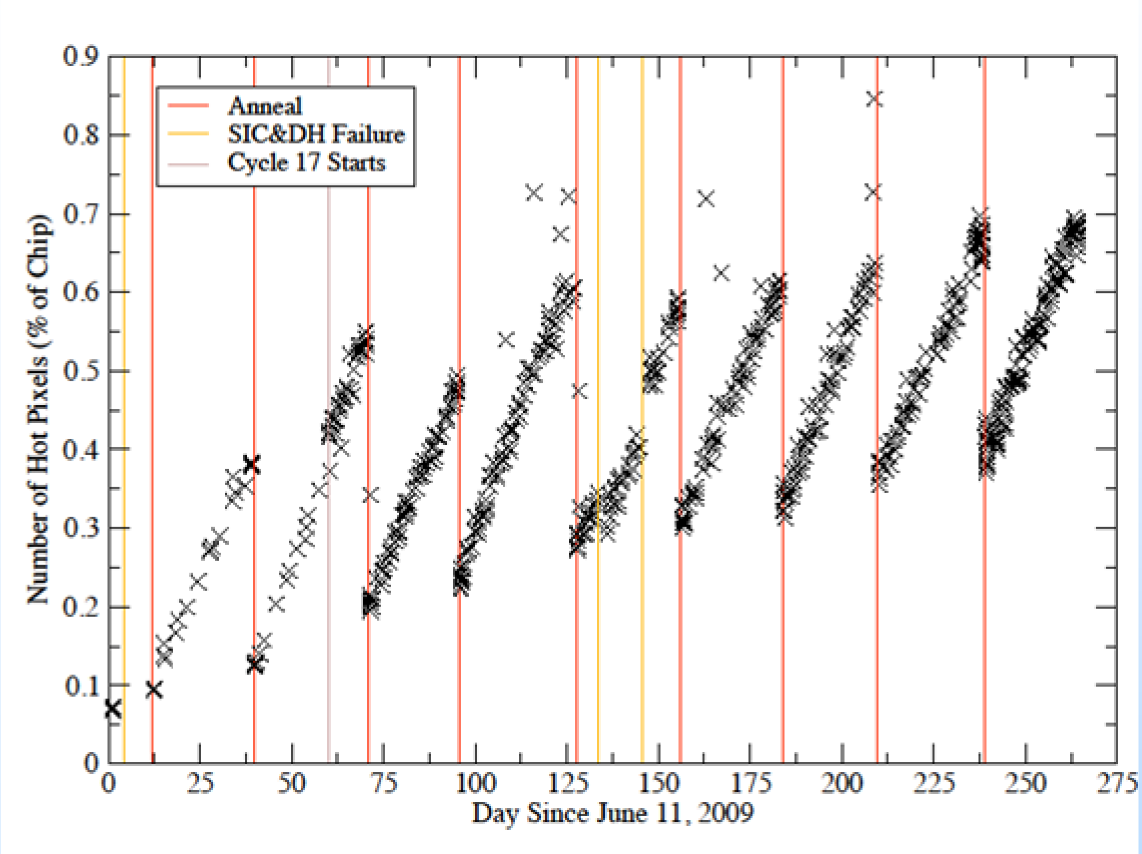
Photo of dewar interior to be added

New Si Technologies & On-Orbit Dark Current Annealing

- **Increasingly, scientific Si sensor applications are able to employ state-of-the-art Si PIN hybrid arrays where previously only charge coupled devices (CCDs) could provide necessary performance**
  - **Si PIN arrays have no charge transfer efficiency issues so are much more robust to proton displacement damage than CCDs**
  - **The dark current levels for Si PIN technology have improved significantly along with their total ionizing dose response**
  - **Proton induced dark current increases are the limiting radiation effect, and in contrast with CCDs, there are no high electric fields to generate hot pixels via electric field enhanced emission from proton induced defects.**
  - **This technology has real potential for future NASA missions.**
- **Scientific Si CMOS sensor arrays under development for flight instruments.**
- **All HST CCDs have exhibited on-orbit dark current annealing after warm-up to quiescent temperatures around 0 C. We do not understand this phenomena although we have reproduced it on the ground via HST/NEPP efforts.**
- **Hence we are leveraging a current DoD program (Joint Milliarcsecond Pathfinder Survey (JMAPS)) with demanding performance requirements in line with typical NASA applications.**

On-Orbit Dark Current Annealing on WFC3 CCD

- **We have ground based proton annealing data (irradiated at -83 C) & on-orbit data for comparison for HST WFC3 e2v CCD**
- **Reason for beneficial annealing at roughly 0 C is not known but observed on many HST CCDs**
  - **Known interstitial related defects anneal at higher temperatures**
- **Current review of Si defect literature indicates some possibilities**
  - **Vacancies are less mobile but can form complex clusters with the midgap defect levels measured by JMAPS.**



Baggett et al., SPIE, 2010.

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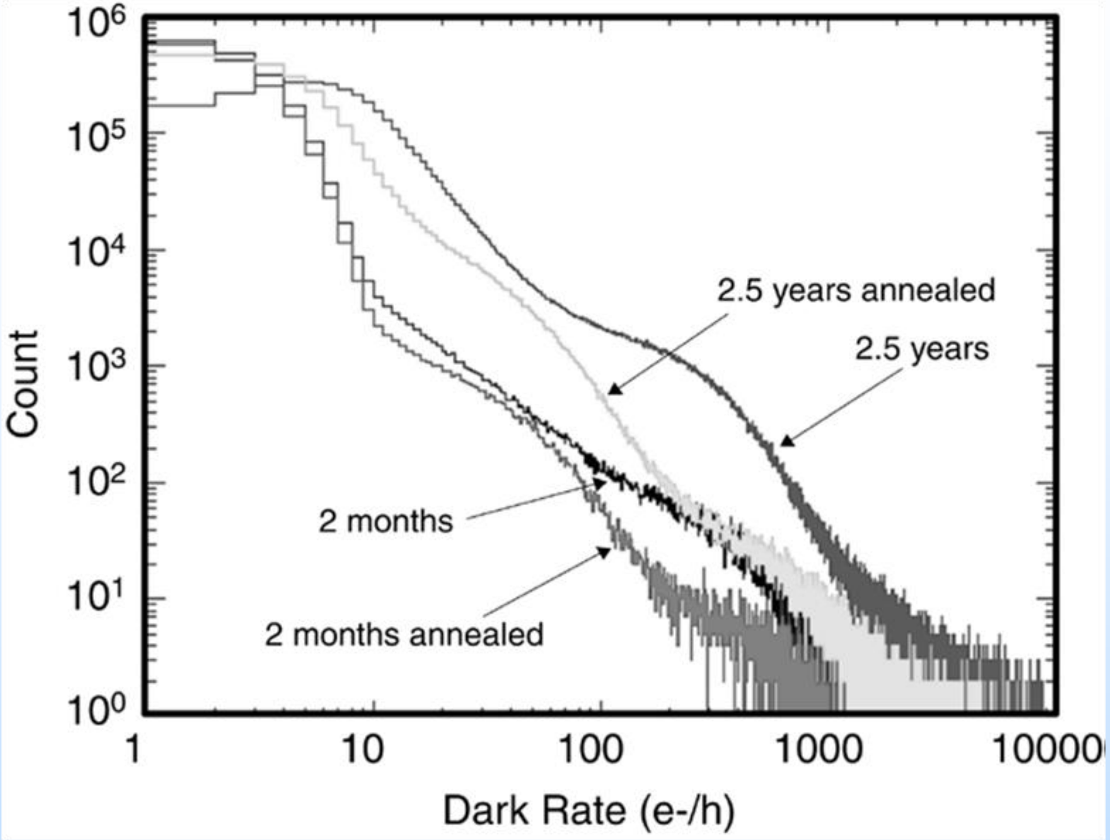
WFC3 Ground Annealing Observations



Marshall et al., TNS 2005.

- **Dark current measurements on CCD 43 pixel populations after 2.5 x 10^9 protons at 63 MeV (2.5 years) show increased dark current means and hot pixel tails.**
- **After annealing by warm up to 300 K, and subsequent cooling for re-measurement at 189 K both the mean dark current and hot pixel populations annealed significantly.**

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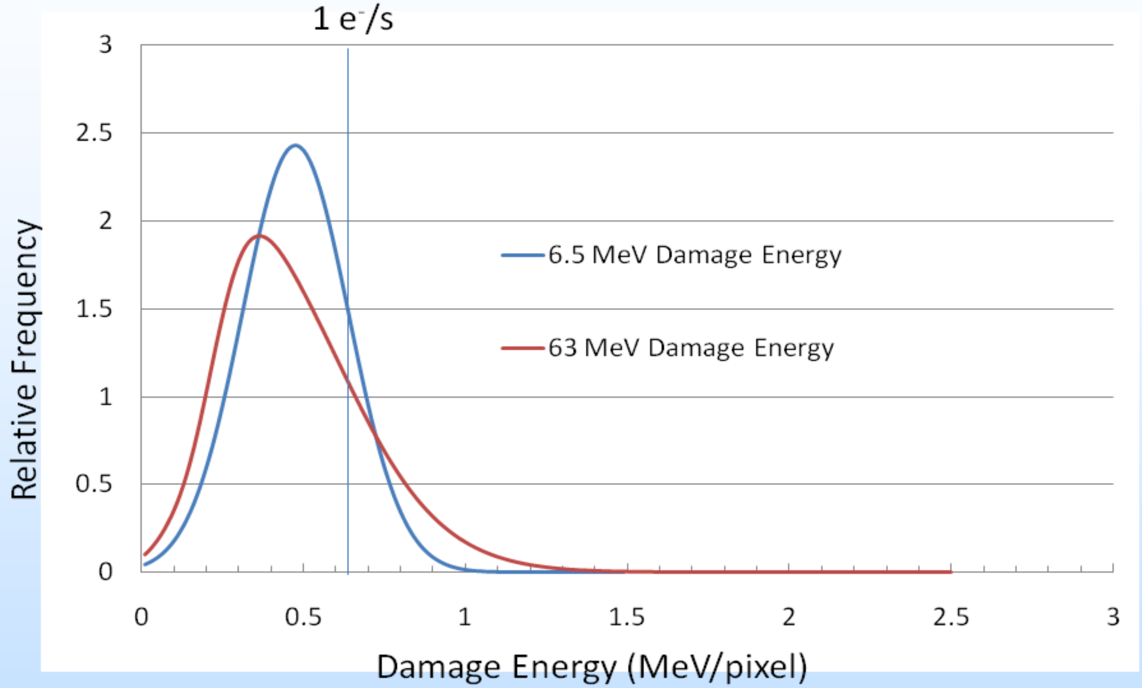
Modeling of Dark Current Distributions

Histograms of Calculated Damage Energy Distributions for 6.5 vs. 63 MeV Protons
Mean damage equal for 2 cases



Damage energy calculation method after Marshall et al., TNS 1990.

- **Recent JMAPS dark current data on Si PINs also shows significant annealing at 300 K in line with our recently re-analyzed WFC3 CCD data.**
- **Another ‘lessons learned’ of value to NASA from JMAPS is how to proceed with proton testing when activation of the package obscures results at the higher proton energies of interest.**
    - **Note that NEPP also has experience with damage energy calculations.**

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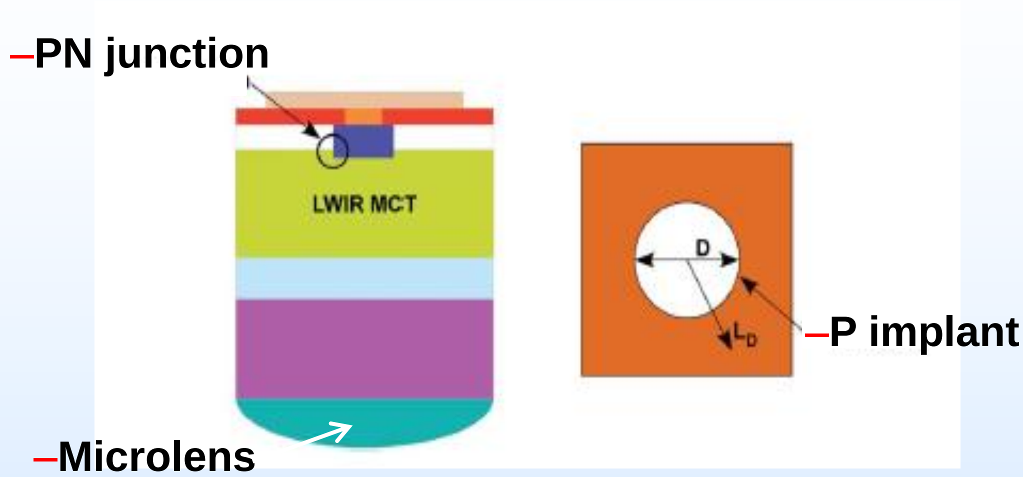
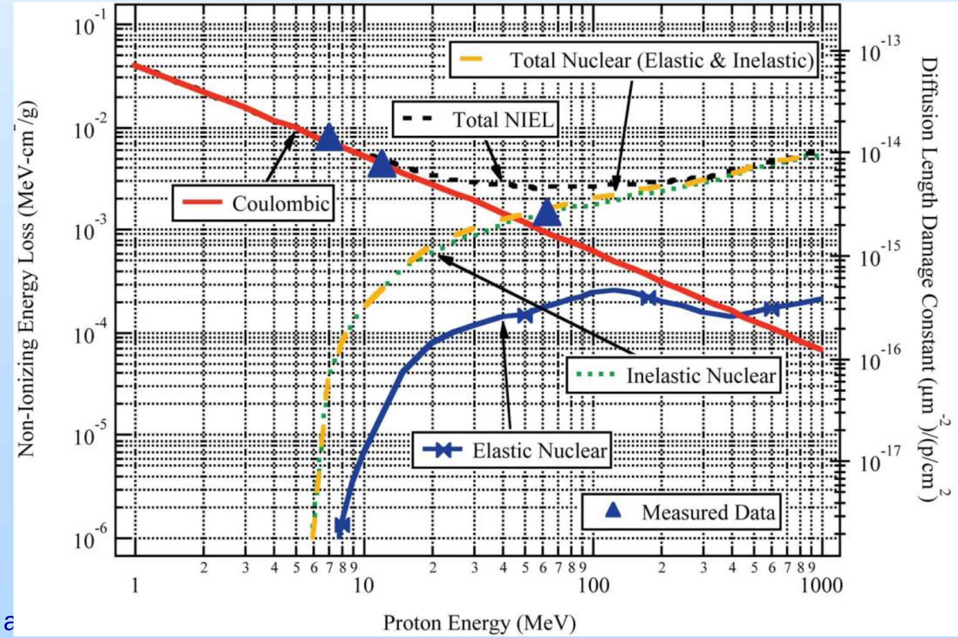
Radiation Hardened LWIR HgCdTe Technology



–Pictorial of an individual LWIR detector. Use of a microlens to collect incoming photons over the entire pixel area in conjunction with a p-implant that restricts the active diode volume results in good QE and lower dark current (before and after irradiation.)

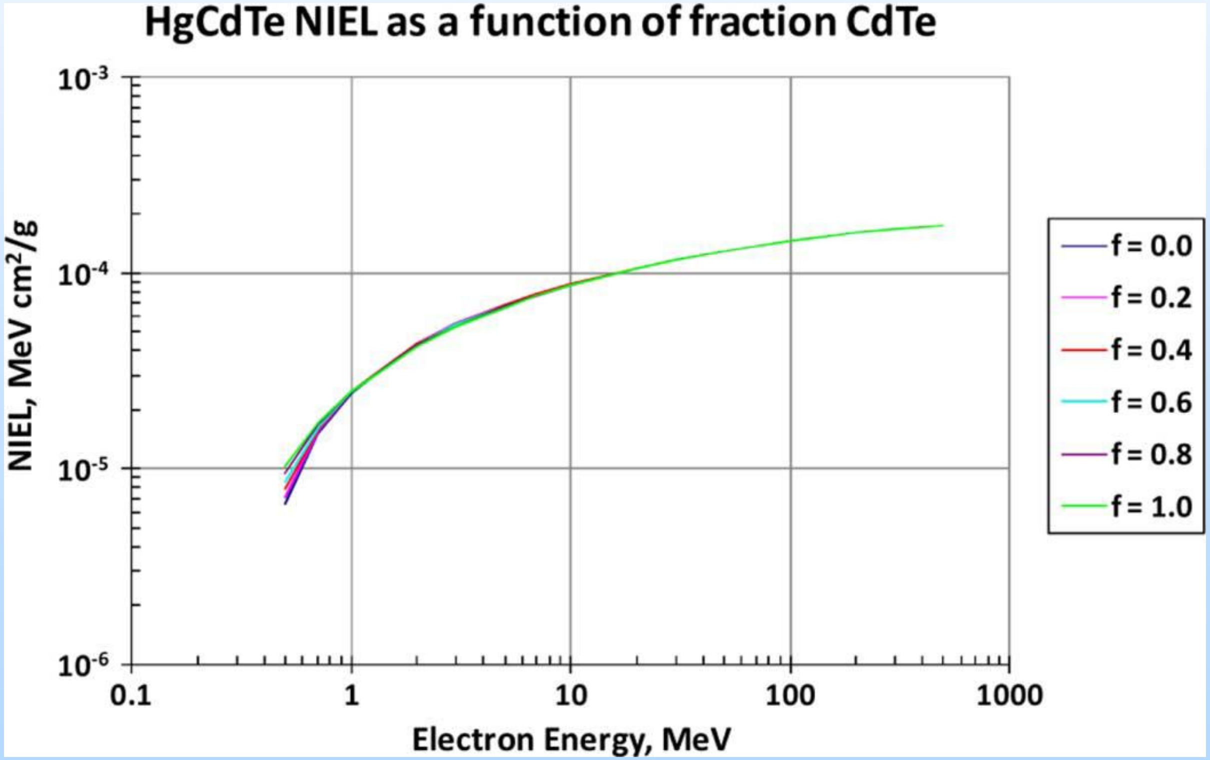
- Previous AFRL/NEPP effort demonstrated hardness out to 600 krad(Si) from 63 MeV protons
  - Application dependent & limited by HgCdTe response
  - We characterized a wide range of diode diameters so we have data relevant to development of arrays for NASA applications & understanding mechanisms.



NonIonizing Energy Loss (NIEL) in HgCdTe

- Currently no data exists to demonstrate validity of electron / proton non-ionizing energy loss (NIEL) correlation for any performance parameter in HgCdTe material system.
  - We have detailed proton data for both majority carrier effect (dark current) and minority carrier effect (responsivity) for this technology.
    - NIEL correlation verification required for both classes of rad effects.

- Current IRAD effort will pave the way for future electron testing
- Follow-on IRAD proposal submitted.



Insoo Jun, JPL

Preliminary FY12 Plans

- Continue latchup characterization and modeling as a function of temperature for TowerJazz CA18HD process favored by ROIC and Si CMOS sensor development
  - Submitted Phase 1 IRAD to develop cryogenic laser latchup test capability
- Continue study of Si displacement damage annealing as it applies to dark current
  - Review available on-orbit data
  - Leverage SoloHI proton testing on scientific CMOS sensor arrays under development
- Further our understanding of 1/f noise in ROICs and emerging Si sensor arrays
  - Other generic topics of interest include possible ELDRS effects in Si sensors
- Take advantage of sensor test program opportunities at AFRL as they present.
- Take advantage of any IR lessons learned from electron testing and modeling of radiation hardened LWIR HgCdTe array
  - Submitted Phase 1 IRAD to develop cryogenic electron test capability